REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0705-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 9/22/00	3. REPORT TYPE AND DATES COVERED Final Report 06/01/95-05/31-98

4. TITLE AND SUBTITLE Epitaxial Growth and Fabrication of Highly Strained Heterostructures	DAAH04-95-1-0329
6. AUTHOR(S) Steve P. DenBaars	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Materials Department College of Engineering University of California Santa Barbara, CA 93106-5050	8. PERFORMING ORGANIZATION REPORT NUMBER 8-442490-23040
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING/MONITORING AGENCY REPORT NUMBER ARO 32941.1-EL-YIP

11. SUPPLEMENTARY NOTES
The Views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department Of the Army position, policy and decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Room temperature (RT) pulsed operation of **blue** nitride based multi-quantum well (MQW) laser diodes grown on c-plane sapphire substrates were achieved. Emission wavelengths as long as 425nm were obtained. Atmospheric pressure MOCVD was used to grow the active region of the device which consisted of a 10 pair $In_{0.21}Ga_{0.79}N$ (2.5nm)/$In_{0.07}Ga_{0.93}N$ (5nm) InGaN MQW. The threshold current density was reduced by a factor of 2 from 10 kA/cm^2 for laser diodes grown on sapphire substrates to 4.8 kA/cm^2 for laser diodes grown on LEO GaN on sapphire. These results show that a reduction in nonradiative recombination from a reduced dislocation density leads to a higher internal quantum efficiency. The researchers would like to thank the generous support and guidance of Dr. John Zavada. Further research on lateral epitaxial overgrowth (LEO) is needed to extend the wavelength to 490nm which is required for numerous bio-chemical sensing applications.

14. SUBJECT TERMS Blue nitride, Multi-quantum well (MQW), Laser diodes, MOCVD	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

Final Report for ARO Project

DAAH04-95-1-329
Dr. John Zavada
Project Manager

U.S. Army Research Office
P.O. BOX 12211
RESEARCH TRIANGLE PARK, NC 27709-2211

EPITAXIAL GROWTH AND FABRICATIONOF HIGHLY STRAINED HETEROSTRUCTURES

S.P. DenBaars (P.I.)
Department of Electrical and Computer Engineering and Materials
University of California, Santa Barbara, CA 93106

ABSTRACT

Room temperature (RT) pulsed operation of **blue** nitride based multi-quantum well (MQW) laser diodes grown on c-plane sapphire substrates were achieved. Emission wavelengths as long as 425nm were obtained. Atmospheric pressure MOCVD was used to grow the active region of the device which consisted of a 10 pair $In_{0.21}Ga_{0.79}N$ (2.5nm)/$In_{0.07}Ga_{0.93}N$ (5nm) InGaN MQW. The threshold current density was reduced by a factor of 2 from 10 kA/cm^2 for laser diodes grown on sapphire substrates to 4.8 kA/cm^2 for laser diodes grown on LEO GaN on sapphire. These results show that a reduction in nonradiative recombination from a reduced dislocation density leads to a higher internal quantum efficiency. The researchers would like to thank the generous support and guidance of Dr. John Zavada. Further research on lateral epitaxial overgrowth (LEO) is needed to extend the wavelength to 490nm which is required for numerous bio-chemical sensing applications.

I. INTRODUCTION

The development of blue lasers offers great potential for high density information storage, medical devices, and full-color displays. Since the report of the first RT pulsed operation of nitride based laser diodes by researchers at Nichia Chemical Industries two years ago [1] a handful of research groups in Japan and the United States have reported

blue laser operation . Despite the significant progress by Nichia and others, the actual lasing mechanism and its relationship to the structural and electrical properties of these materials is not well understood. In this study we report on the growth of InGaN MQW and the properties of laser diodes made with InGaN MQW active regions.

RESULTS

InGaN multiple-quantum-well (MQW) laser diodes were grown by MOCVD in a two-flow horizontal reactor at both atmospheric and low pressure. In preparation for patterning a subsequent regrowth, a 2 μm thick GaN seed layer was grown on a c-plane sapphire substrate. A 2000 Å SiO_2 mask was patterned into stripes, oriented in the $<1\bar{1}00>_{GaN}$ direction, defining a 5 μm mask opening with a periodicity of 20 μm. After ~ 6 μm of LEO GaN growth on the SiO_2 mask, the GaN stripes grew laterally and coalesced, forming a flat surface. The conditions for growth and coalescence of the LEO GaN are described elsewhere.[20] Next, the InGaN MQW laser structure was grown on both LEO GaN and on 2 μm GaN on sapphire. The structure had an active region consisting of a 3 period $In_{0.13}Ga_{0.87}N$ (40 Å) /$In_{0.04}Ga_{0.96}N$:Si (85 Å) MQW followed by a 200 Å $Al_{0.2}Ga_{0.8}N$:Mg cap. The n and p-type cladding regions surrounding the active region consisted of 25 Å $Al_{0.2}Ga_{0.8}N$ / 25 Å GaN superlattices with a total thickness of 0.45 μm. The cladding regions were Si-doped for the n-cladding and Mg-doped for the p-cladding. A 0.1 μm GaN:Mg layer was used as a contact layer and a 0.1 μm $In_{0.05}Ga_{0.95}N$:Si layer was used beneath the lower n-type cladding as a compliance layer.

Laser diodes were fabricated above the SiO_2 mask in the nearly dislocation-free wing regions, as well as above the coalescence fronts of the LEO GaN stripes. The laser cavity was oriented parallel to the direction of the SiO_2 stripes. Laser facets were formed by Cl_2 reactive ion etching (RIE) of 45 μm wide mesas of various lengths ranging from 400 μm to 1600 μm and p-contact stripes were patterned on these mesas with widths ranging from 5 μm to 15 μm. The structure was etched around the p-contact stripe through the p-cladding for index guiding. The n and p-contacts were formed by electron beam evaporation of Ti/Al and Pd/Au, respectively.

Figure 1 shows cross-section TEM micrographs of the coalescence region. There are few or no threading dislocations generated at the coalescence fronts. This high quality coalescence results from low wing tilts of the laterally growing stripes. The LEO wings have a tilt of 0.1° relative to the underlying seed material, which was measured using x-ray diffraction as described earlier.[18]

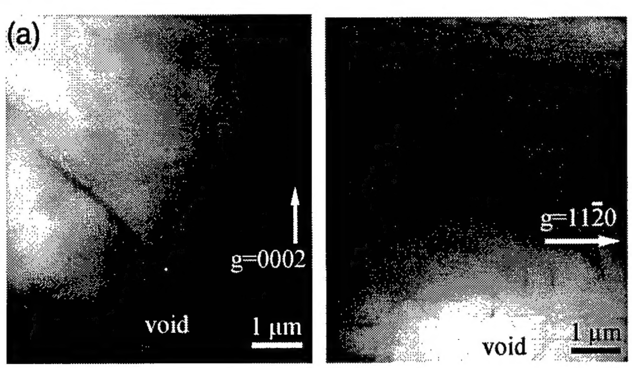

Figure 1: Bright-field cross-section TEM micrographs of a coalescence front viewed with (a) g = 0002 and (b) g = $11\bar{2}0$ two-beam conditions.

The threading dislocations in LEO GaN on sapphire are predominantly located in 'window' stripes every 15 μm, whereas structures on sapphire substrates have a more uniform dislocation distribution over the wafer. The dislocation distribution dominates the size of features in the surface morphology. Atomic force microscopy (AFM) was used to investigate the surface morphology for lasers grown on LEO GaN and laser grown on sapphire as seen in Figure 2. The surface morphology is drastically different for the two structures. The lasers on sapphire show small spirals uniformly distributed whereas on the LEO GaN the laser structure exhibits large spirals. These spirals grow in size until they meet another spiral. Each of these spirals is formed around a threading dislocation with a screw component. In the case of the LEO GaN, the threading dislocations are contained in the window region and are absent in the wing region. This is why all the spirals in the LEO case initiate in the narrow window regions and can grow quite large over the wing until it meets another spiral associated with a screw component threading dislocation from an adjacent window region forming a flat "trench-like" feature. In the case of the laser on sapphire, the spiral remain small because they meet neighboring spirals much more quickly due to the higher and more uniform dislocation distribution.

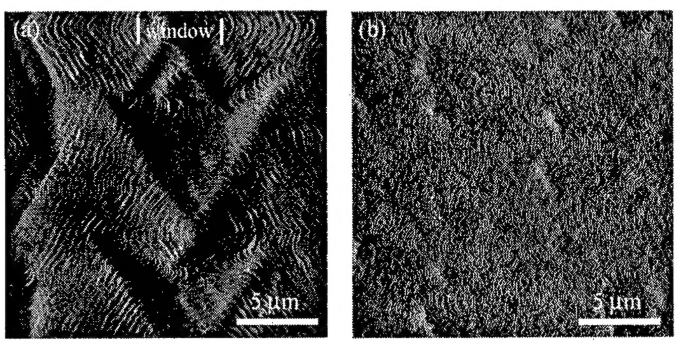

Figure 2: 20x20 μm2 amplitude AFM images of (a) a laser structure on LEO (b) a laser structure on sapphire. Note: The LEO stripes are running vertically.

Figure 3 shows the typical light output per uncoated facet of a laser diode grown on LEO GaN and a laser diode grown on GaN/sapphire as a function of forward current under pulsed operation. The minimum threshold current density was reduced by a factor of 2 from 10 kA/cm^2 for laser diodes grown on sapphire to 4.8 kA/cm^2 for laser diodes grown on LEO GaN on sapphire. The laser diodes on the LEO GaN showed this low threshold current density of 4.8 kA/cm^2 both above the SiO_2 mask regions and above the coalescence fronts of the LEO GaN. This reduction in threshold current density is attributed to a reduction in nonradiative recombination due to the lower dislocation density in the LEO GaN.

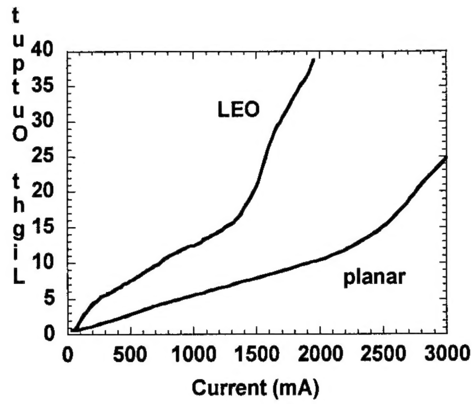

Figure 3: Typical light output per uncoated facet as a function of current for a laser diode grown on LEO GaN and a laser diode grown on sapphire.

Figure 4 shows the reciprocal of external differential quantum efficiency as a function of length for laser diodes grown on sapphire and LEO GaN. The external differential quantum efficiency of the laser diode increases with increasing internal quantum efficiency or decreasing internal optical loss as seen in the following relationship[21],

$$\eta_d = \eta_i \frac{\alpha_m}{\langle \alpha_i \rangle + \alpha_m} \tag{1}$$

where η_d is the external differential quantum efficiency, η_i is the internal quantum efficiency, α_m is the mirror loss and α_i is the internal optical loss of the laser. The mirror loss can be defined as

$$\alpha_m = \frac{1}{L}\ln\left(\frac{1}{R}\right) \tag{2}$$

where L is the length and R is the facet reflectivity. R is estimated to be approximately 0.053 for RIE etched facets.[22] Substituting Eqn. (2) into (1) and rearranging gives

$$\frac{1}{\eta_d} = \frac{1}{\eta_i} + \frac{\langle \alpha_i \rangle}{\eta_i \ln\left(\frac{1}{R}\right)} L \tag{3}$$

The internal quantum efficiency can be extracted from the y-intercept of Fig. 4 using Eqn. (2). The increase in external differential quantum efficiency seen in the lasers on LEO GaN compared to those on sapphire is due to a increase in the internal quantum efficiency from 3% to 22%. As mentioned, the reduced reverse bias leakage current in p-n junction diodes suggests the presence of mid-gap states due to threading dislocations.[23] These mid-gap states provide nonradiative recombination centers thereby decreasing the internal quantum efficiency. Reducing the dislocation density, and hence the mid-gap states, will result in an increased internal quantum efficiency. The same effect is also seen in the spontaneous emission portion of L-I curve below threshold in Fig. 2 as well as in LEDs fabricated on LEO GaN,[11,24] where the radiative efficiency increases with decreasing dislocation density.

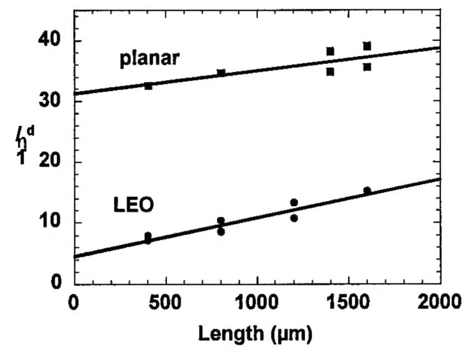

Figure 4: Inverse external differential quantum efficiency as a function of device length.

SUMMARY AND ACKNWOLEDGEMENTS

In summary, InGaN multi-quantum well laser diodes have been fabricated on fully coalesced laterally overgrown GaN on sapphire. The wing regions as well as the coalescence regions of the LEO GaN contain few or no threading dislocations. The threshold current density was reduced by a factor of 2 from 10 kA/cm^2 for laser diodes grown on sapphire substrates to 4.8 kA/cm^2 for laser diodes grown on LEO GaN on sapphire. These results show that a reduction in nonradiative recombination from a reduced dislocation density leads to a higher internal quantum efficiency. The researchers would like to thank the generous support and guidance of Dr. John Zavada.

References

[1] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemeto, M. Sano, and K. Chocho, Proc. Int. Conf. on Nitride Semicond., S-1, p. 444 (1997).

[2] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemeto, M. Sano, and K. Chocho, Appl. Phys. Lett. **72**, 211 (1998).

[3] K. Ito, K. Hiramatsu, H. Amano, I. Akasaki, J. Cryst. Growth **104**, 533 (1990).

[4] D. Kapolnek, S. Keller, R. Vetury, R. D. Underwood, P. Kozodoy, S. P. DenBaars, and U.K. Mishra, Appl. Phys. Lett. **71**, 1204 (1997).

[5] T. S. Zheleva, O.-H. Nam, M. D. Bremser, and R. F. Davis, Appl. Phys. Lett. **71**, 2472 (1997).

[6] O.-H. Nam, M. D. Bremser, T. S. Zheleva, and R. F. Davis, Appl. Phys. Lett. **71**, 2638 (1997).

[7] H. Marchand, J. P. Ibbetson, P. T. Fini, P. Kozodoy, S. Keller, J. S. Speck, S. P. DenBaars, and U. K. Mishra, MRS Internet J. Nitride Semicond. Res. **3**, 3 (1998).

[8] A. Usui, H. Sunakawa, A. Sakai, and A. A. Yamaguchi, Jpn. J. Appl. Phys. **36**, L899 (1997).

[9] A. Sakai, H. Sunakawa, and A. Usui, Appl. Phys. Lett. **71**, 2259 (1997).

[10] P. Kozodoy, J. P. Ibbetson, H. Marchand, P. T. Fini, S. Keller, S. Keller, J. S. Speck, S. P. DenBaars, and U. K. Mishra, Appl. Phys. Lett. **73**, 957 (1998).

[11] C. Sasaoka, H. Sunakawa, A. Kimura, M. Nido, A. Usui, and A. Sakai, J. Crystal Growth **189/190**, 61 (1998).

[12] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Matushita, and T. Mukai, MRS Internet J. Nitride Semicond. Res. **4S1**, G1.1 (1999).

[13] R. Vetury, H. Marchand, J. P. Ibbetson, P. Fini, S. Keller, J. S. Speck, S. P. DenBaars, and U.K. Mishra, Proceedings of the 25th Int. Symp. Comp. Semicond., Nara, Japan, 1998.

[14] G. Parish, S. Keller, P. Kozodoy, J. P. Ibbetson, H. Marchand, P. T. Fini, S. B. Fleischer, S. P. DenBaars, U. K. Mishra, and E. J. Tarsa, Appl. Phys. Lett. **75**, 247 (1999).

[15] H. Marchand, J. P. Ibbetson, P. Fini, S. Chichibu, S. J. Rosner, S. Keller, S. P. DenBaars, J. S. Speck, and U.K. Mishra, Proc. 25th Int. Symp. Comp. Semicond., Nara Japan, 1998.

[16] K. Tsukamoto, W. Taki, N. Kuwano, K. Oki, T. Shibata, N. Sawaki, and K. Hiramatsu, Proc. 2nd Int. Symp. On Blue Laser and Light Emitting Diodes, Kisarazu, Chiba, Japan, 1998, p. 488-491.

[17] P. Fini, J. P. Ibbetson, H. Marchand, L. Zhao, S. P. DenBaars, and J. S. Speck, unpublished (1999).

[18] S. Keller, U. K. Mishra, S. P. DenBaars and W. Seifert, Jpn. J. Appl. Phys. **37**, L431 (1998).

[19] T. Sugahara, M. Hao, T. Wang, D. Nakagawa, Y. Naoi, K. Nishino and S. Sakai, Jpn. J. Appl. Phys. **37**, L1195 (1998).

[20] P. Fini, L. Zhao, B. Moran, M. Hansen, H. Marchand, J. P. Ibbetson, S. P. DenBaars, U.K. Mishra, and J. S. Speck, Appl. Phys. Lett. **75**, 1706 (1999).

[21] L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits (John Wiley & Sons,* Inc., New York, 1995).

[22] M. P. Mack, G. D. Via, A. C. Abare, M. Hansen, P. Kozodoy, S. Keller, J. S. Speck, U. K. Mishra, L. A. Coldren, and S. P. DenBaars, Electron. Lett. **34**, 1315 (1998).

[23] For a review on physical properties of threading dislocations in GaN please see J.S. Speck and S. J. Rosner, to be published in Physica B (1999).

[24] M. Hansen, P. Fini, A. C. Abare, L. A. Coldren, J. S. Speck, and S. P. DenBaars, unpublished (1999).